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# Application of thermoelectric ageing models to polymeric insulation in cable geometry

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## Abstract

The life expressions of models of insulation ageing are functions of temperature and field as well as material parameters. A methodology is presented that allows these models to be applied to a cable geometry in which there is a radial variation of both field and temperature. In this way material parameters can be extracted from cable data. The methodology is illustrated using one such model and the parameters deduced from cable failure distributions are compared with those obtained for thin films. This comparison allows conclusions to be drawn about how the ageing process affects specimens of the same material with different volumes.

## Keywords

Modelling, Ageing, Failure, Cable Geometry, Analysis of Cable Lifetimes

## 1. Introduction

Polymeric materials are used as electrical insulators in a wide range of industrial applications, from thin films in capacitors to thick insulation layers in high voltage power cables. In all cases the service life of the dielectric is of major commercial interest and consequently a number of theoretical models have been developed with the aim of relating the working lifetimes of dielectric polymers to the electrical and thermal stress experienced. Current interest has focussed on physical theories proposed by: by L.A. Dissado, G.C. Montanari and G. Mazzanti [1-4], T.J. Lewis, P.J. Llewellyn, C.L. Griffiths, P.W. Sayers and S. Betteridge [5-13], J.P Crine and J. Parpal [14,15], L. Simoni [16], and J. Artbauer [e.g. 17].

Ageing models such as those mentioned above generally result in a mathematical expression that describes the lifetime of a specimen as a function of the electrical stress, E, and temperature, T it experiences. Other factors related to material properties are also involved. When the specimens under investigation are thin films aged under spatially constant field and temperature conditions, fitting such expressions to lifetime data and conversely predicting lifetimes using them is relatively straightforward. However, in systems such as power cable insulation the situation is more complex. The insulation of a power cable under load experiences a radially varying temperature distribution due to Joule heating of the conductor [18,19], as well as a radially varying electrical stress distribution, which will be different for AC and DC applied voltages [18,19,20]. The difference in AC and DC electrical stress profiles arises from the fact that in the AC case the stress profile is controlled by the permittivity of the insulation, which depends only very weakly on

temperature – at least for the range of temperatures typically experienced by cable insulation. In the DC case the electrical stress is controlled by the conductivity, which is strongly dependent on both temperature and stress, and this can lead to a situation in which the field stress experienced by the insulation is not necessarily largest close to the cable core. This effect is described briefly in the following sections. The radial variation in E and T makes using the ageing models to either fit or predict lifetime data in cable ageing experiments more difficult than in the thin film case.

In the first instance it may seem that all that is required to convert the life models to cable geometry is to calculate the region where the electric field and temperature is largest and then apply them to that region as a cylindrical shell. However such is not the general case. For DC power cables in particular it cannot always be assumed that the region where the temperature is highest is the region where the electric field is highest [21]. In the second place the region at risk depends upon the physics of the ageing process, for example in [1-4] this is assumed to be the region of highest space charge concentration, in [5-13] it is assumed to be a layer of high electro-mechanical stress, and in [15, 16] regions of free volume that allow high local currents. Finally there are the material factors that are involved in ageing, such as the activation energy for the process, the susceptibility of the local regions to the action of the field, and the amount of local damage needed for imminent failure to be initiated. All of these may be distributed in value [22]. There may also be radial differences in morphology that will affect the factors controlling ageing. Sample ageing will take place most rapidly in the region where the combined factors of temperature, field, and material properties are worse. It is therefore necessary to develop a method that can take account of such

variations, and this cannot be restricted to a single shell but will have to involve the whole of the cable.

In the following sections we describe a general methodology that allows ageing models to be applied to cable geometry. In principle this methodology allows prediction of cable lifetime using model parameterisation from thin films, however the unknown volume dependence of the thin film parameters makes this procedure impossible at present. Instead the method is used to derive parameter values appropriate to the cable volume from cable failure data. This approach is illustrated using the DMM [1-4] lifetime expression. In this work the method is applied to data from ac ageing as this simplifies the calculation and was the only data available to the authors in sufficient quantity to make an analysis feasible. The method is however, equally applicable to ageing in a dc field provided that the difference in the radial variation of the temperature and field is taken into account. The calculation is also simplified by focussing upon the characteristic values of the parameters of the life expression. These are derived and compared to those obtained for thin films and the differences commented upon. Calculations that take account of the distribution in value of the material parameters in order to fit the experimental life distributions [22] will be reported at a later date.

## 2. Method

All theoretical models yield an expression for the lifetime in terms of temperature, electric field and mechanistic parameters that may be dependent upon the material and/or the electrode-material interface. In the case of cable insulation one or both of the temperature and electric field will vary radially from the conductor to the outer

electrode. The theoretical life expressions will therefore yield different thermoelectric lifetimes depending on the radial location of the region considered. Some regions will therefore reach the endpoint of ageing before others. In order to relate the theoretical models to the service life of the cable, it is therefore necessary to decide upon the condition under which the cable fails – i.e. whether it is necessary for the whole cable to age to a defined end-point, or whether it is sufficient for only one region to reach this degree of ageing. In the latter case cable failure will be initiated in the region that has reached a critical level of ageing and rapidly proceed to completion. The philosophy of the current ageing theories is in accord with the latter viewpoint and it is therefore the one that we shall adopt here.

### 2.1 Shell model

The radial variation of temperature and electric field is allowed for by dividing the cable insulation into a series of thin films within which temperature and field can be considered constant. Each shell can therefore be assigned a lifetime using the theories appropriate to thin films under uniform field and constant temperature.

Figure 1 shows a cable with a typical simple design, comprising a cylindrical core covered in a layer of insulation. An example 'shell' at radius $r_i$ is shown. Such shells can be of equal thickness, or equal volume. None of the ageing models mentioned in the introduction takes account of any of the spatial dimensions of the polymer specimen, or those of the test electrodes. In fact, depending on the mechanisms of ageing, at least one of these factors is likely to be important to the lifetime of a polymer specimen. It is commonly assumed that ageing is a bulk process, in which case it is often argued that the volume of a specimen must affect its lifetime (e.g.[23])

and this is discussed further in section 4.2. Considering shells of equal volume means that the effect of volume on ageing will be the same for each, and this option is therefore used here.

### 2.2 Radial dependence of E and T

The field and temperature experienced by each of the shells described above is a function of the shell's radial position, $r_i$. The temperature of a shell at radius $r_i$ can be written as (see [18,19]):

$$T(r_i) = T_1 + \left( \frac{W \times Th}{2\pi} \ln\left( \frac{R_O}{r_i} \right) \right) \quad (1)$$

where W is the power dissipated per unit length by the core under load and Th is the combined thermal resistivity of the insulation and any outer layers. $R_O$ is the cross sectional radius of the cable as shown in figure 1, and $T_1$ is the temperature of the outside of the cable –i.e. the ambient temperature.

Under AC conditions, the RMS electrical stress experienced by the same shell is e.g. [20]:

$$E(r_i) = \frac{V}{r_i \ln\left( \frac{R_O}{R_I} \right)} \quad (2)$$

V is the voltage applied to the cable core, $R_O$ is as defined above and $R_I$ is the cross sectional radius of the cable core. The above expression shows that in the AC case, the electrical field strength in cable insulation is always largest close to the cable core.

If a DC voltage is applied to the cable core, the electrical stress profile is more complicated, and is given by [18,20]:

$$E(r_i) = \frac{V\delta\left(\frac{r_i}{R_O}\right)^{\delta-1}}{R_O\left(1-\left(\frac{R_I}{R_O}\right)^{\delta}\right)} \tag{3}$$

where all symbols have their previous meanings, and δ is given by

$$\delta = \frac{a\frac{W\times Th}{2\pi}+\frac{mV}{R_O-R_I}}{\frac{mV}{R_O-R_I}+1} \tag{4}$$

In equation 4, a and m are constants in equation (5) describing the resistivity, ρ of the insulation in terms of electrical field, E and temperature T:

$$\rho = \rho_0 \exp(-aT)\exp(-mE) \tag{5}$$

In equation (5) $\rho_0$ is resistivity at T=0 and for vanishingly small E.

The expression for E(r) in the DC case leads to a situation in which the electrical field strength may actually be largest at the outer edge of cable insulation systems for some values of current [18,20,21].

### 2.3 Predicting Cable Lifetimes

The parameters determined for the life expressions of current models are values appropriate to the characteristic life in a lifetime distribution [22]. Substituting for the

temperature $T(r_i)$ and field $E(r_i)$ will therefore give the characteristic life of the shell if its volume is the same as that of the specimens for which the parameters are derived. The probability of survival to time t of the 'i'th shell is thus given by

$$P_S(i) = \exp\left(-\left[\frac{t}{L_i}\right]^{\beta}\right) \tag{6}$$

where β is the time exponent of the Weibull distribution [23,24] that fits the thin sample data. Of course an alternative distribution could be used if applicable. The probability of survival of the whole cable is given by the joint probability of survival of all the shells, under the assumption that a failure initiated in any one of them is sufficient to fail the whole cable. This gives equation (7),

$$P_F = 1 - P_S = 1 - \prod_i P_S(i) \tag{7}$$

The resulting failure distribution $P_F$ can be analysed to determine the characteristic life of the whole cable and the failure time distribution [22]. There is however a drawback to carrying through this approach. In general it will be difficult to equate the shell volume to that of the specimens used in the parameterisation of the life expression. If this is not possible the thin film parameterisation cannot be assumed to apply to the cable shell, and in the absence of a measured or theoretical size dependence the parameters cannot be modified appropriately. Of course equation (7) could be taken to refer to a cable length small enough that the shell volumes are the same as the thin films. The whole cable survival probability would then be given by

$$P_S(cable) = P_S(section)^{\frac{l(cable)}{l(section)}} \quad (8)$$

where *l*(cable) is the cable length and *l*(section) is the section length as defined above. Even this approach is only possible if the volume of the thin film samples is known and we assume that the size effect is in fact a volume effect rather than one related to electrode area or sample thickness. In the light of these difficulties we have adopted a different approach described in the next section.

**2.4 Parameterising life expressions from cable data**

In this approach we relate observed cable data to life expression parameters appropriate to the complete insulation volume of the cable. In this section we shall denote the characteristic lifetime of the cable by B63, which is defined as the time at which a fraction ($1-e^{-1}$) equal to 63.2% of the samples have failed. The value of B63 for cables can be obtained from their lifetime distribution in exactly the same way as for thin films. However fitting it to the theoretical life expressions is more complex than for thin films. In the thin film case it is only necessary to fit the expressions to a set of lines giving the T and E dependence of the characteristic life (e.g. [1-4]). In the case of cables each of the shell life expressions is a function of the model parameters and a different E and T value depending on its radial position. To find values for the parameters relevant to a particular set of cable specimens, the shell expressions must be combined, and fitted to experimental ageing data. A method for combining N shell lifetime expressions in order to fit them to the characteristic lifetime at each experimental condition is described here.

It is assumed that in cable insulation of volume VC made up of N shells, failure in any one of the shells will cause the whole insulation to fail. In this case, the following equation links the probability of survival of the whole insulation to the probability of survival of N constituent shells.

$$P_S(C) = \prod_{i=1}^{N} P_S(S)_i \tag{9}$$

Here, $P_S(C)$ is the probability of survival at a given time of the whole insulation. $P_S(S)$ is the probability of survival of a constituent shell. Each shell has a volume VS=VC/N.

The time to failure distributions resulting from ageing tests on polymer specimens are commonly assumed to be Weibull distributions with a shape parameter, β, which is characteristic of the ageing process e.g. [22-24]. This assumption is reasonable if a failure in polymeric specimens can be assigned to the 'weakest' region of polymer, where ageing proceeds faster than in any other. Assuming, therefore, that $P_S(C)$ and $P_S(S)$ are Weibull distributions with the same β value, they are given by e.g.[24].

$$PS(C) = \exp\left(-\left[\frac{t}{B63}\right]^{\beta}\right) \tag{10}$$

$$PS(S) = \exp\left(-\left[\frac{t}{L_i}\right]^{\beta}\right) \tag{11}$$

Here t is time, B63 is the characteristic lifetime of a set of cables aged under the same experimental conditions and $L_i$ is the characteristic lifetime of a set of shells of insulation all aged under one particular condition. β in equation (10) is the shape

parameter of the time-to-failure distribution from the cable ageing experiments, and in equation (11) is the shape parameter of the distribution of the shell times-to-failure. It has been assumed that the values of β in the above equations are the same. This may not necessarily be the case depending upon the origin of β [22], but the introduction of a difference between its value for the shell and the cable would require more knowledge than we have at present and hence is not justified.

By substituting equations (10) and (11) into equation (9), an expression can be derived for the characteristic lifetime of cable insulation, B63 in terms of the characteristic lifetimes, $L_i$, of a set of insulation shells.

$$\frac{1}{B63^{\beta}} = \sum_i \left( \frac{1}{L_i{}^{\beta}} \right) \qquad (12)$$

In this case, B63 is the characteristic lifetime of a cable set, and $L_i$ can be replaced with an expression for the lifetime of the 'i'th shell. Equation (10) can therefore be used to fit the chosen expression to experimental B63 values in order to obtain parameter values.

The parameter values obtained from fitting equation (12) will necessarily depend on the volume of the cable insulation through B63, just as in the case of thin films the parameters depend upon the film volume [24]. However, using equation (12) means that the parameter values must also have a dependence on the shell volume (or equivalently a dependence on N), since the probabilities $P_S(S)$ in equation (9) are volume dependent. Parameters that depend on both VC and N have the disadvantage that direct comparisons between cable and film experiments are then difficult, since

the parameters from film experiments will only depend on the total film insulation volume – equivalent to VC for cables.

To get parameter values from cable experiments that only depend on VC, it is necessary to 'scale up' the probability of failure of each shell to the total insulation volume. In other words, it is necessary to determine an expression for the probability of failure that each shell would have if it had the volume of the whole insulation. This is equivalent to the probability of failure of a shell, with volume VC, comprising N shells each experiencing the same E and T conditions. This can be obtained using an expression of the same form as equation (9):

$$P_S(SS) = \prod_{i=1}^{N} P_S(S)_i \qquad (13)$$

Here $P_S(SS)$ is the probability of survival of the scaled up shell with volume VC, and $P_S(S)$ is the probability of survival of the original shell. Since each value of $P_S(S)$ is the same in this case, this gives

$$P_S(SS)_i = P_S(S)_i^{N} \qquad (14)$$

Taking the product of the PS(SS) values over all the shells now gives the probability of survival of a volume of insulation N times bigger than VC – i.e.

$$P_S(NC) = \prod_{i=1}^{N} P_S(SS)_i \qquad (15)$$

Substituting for $P_S(SS)$ from equation (14) then gives

$$P_S(NC) = \prod_{i=1}^{N} P_S(S)_i^{N} \qquad (16)$$

$P_S(NC)$ is the probability of survival of a cable specimen with a volume N times bigger than VC. To get the probability of survival of cable insulation of volume VC (i.e. of the total cable insulation), equation (14) can be used together with equation (16) to give

$$P_S(C) = P_S(NC)^{\frac{1}{N}} = \left[\prod_{i=1}^{N} P_S(SS)_i\right]^{\frac{1}{N}} \tag{17}$$

Here $P_S(C)$ is the probability of survival of the cable. Using this equation, and assuming again that the probabilities of survival are all Weibull distributions with the same shape parameter, the following equation is derived

$$\frac{1}{B63^{\beta}} = \frac{1}{N}\sum_i \left(\frac{1}{L_i{}^{\beta}}\right) \tag{18}$$

$L_i$ is now an expression for the lifetime of a scaled up shell – i.e. an expression for the lifetime that a shell would have if it had volume VC. It is important to note that $L_i$ in expression (18) has a different meaning to $L_i$ in equation (12), despite the fact that they both relate to the same life expression. Fitting of expression (12) to data results in model parameter values that depend on N, whereas using equation (18) gives parameter values that are independent of N and depend only on the total volume of insulation VC, through B63.

## 3. Application to data

In order to illustrate the methodology described in section2 we will apply it to a specific life expression, namely that of the DMM model [1-4]. This model gives the life, $L_i$, of the 'i'th shell, at temperature $T(r_i)$ and field $E(r_i)$ in the form

$$L_i = \frac{\frac{h}{2kT(r_i)}\exp\left[\frac{-S_d}{k}\right]\exp\left[\frac{H_{dk} - \frac{C_d E(r_i)^{4b}}{2}}{T(r_i)}\right]\left[-\ln\left(\frac{A_{eq} - A^*}{A_{eq}}\right)\right]}{\cosh\left[\frac{K_d - C_d E(r_i)^{4b}}{2T(r_i)}\right]} \tag{19}$$

The factor $A_{eq}$ is defined through expression (20),

$$A_{eq} = \frac{1}{1 + \exp[(K_d - C_d E(r_i)^{4b})/T(r_i)]} \tag{20}$$

There are therefore only six nominally independent parameters in the life expression, b, A*, $H_{dk}$, $S_d$, $K_d$ and $C_d$. This expression is based on the concept that the energy stored in local concentrations of space charge causes a local deformation of the polymer to exceed a critical level at which free volume generation and nano-void coalescence occurs. Failure is then rapidly brought about by partial discharging leading to electrical trees and connection of the void population. The polymer chains are conceived as possessing alternative configurations with the one corresponding to the deformation being energetically unfavourable with respect to the other. The energy difference is $K_d$ (in units of Kelvin). The 'reaction' from one configuration to the other requires a free energy barrier to be exceeded, composed of an activation enthalpy $H_{dk}$ (units of Kelvin) and an activation entropy $S_d$ (units of Kelvin). In the

absence of the space charge produced by the applied field E, the fraction of local configurations in the 'deformed' state will reach an equilibrium value $A_{eq}$. The space charge concentration has been assumed to be proportional to a power b of the applied electric field, (i.e. *local charge* = $q_{loc} \propto E^b$) [1-4] and to modify the energy barrier and energy difference between the alternative configurations via an electro-mechanical energy leading to the energy term $C_dE^{4b}$ in the above expressions. It is assumed that life is terminated when the fraction of configurations in the 'deformed' state reaches a level sufficient for coalescence into voids, starting from an initial non-equilibrium state corresponding to an unaged material. This critical fraction is denoted by A*. The reader is referred to references [1-4] for more detail. Each of the parameters are expected to be essentially independent of temperature, and the role played by the local temperature in the life expression is explicitly defined via equation (19). In AC fields $S_d$ and $H_{dk}$ become frequency dependent [4], whereas in DC fields $S_d$ can be taken to be zero [4] thereby reducing the number of parameters to five.

This expression was chosen here because the parameter values for a number of materials are available in the literature [1-4]. In addition the expression exhibits all the basic features present in the other models – i.e. an activation free energy that must in general involve two parameters, a field effect term involving a composite parameter, here $C_d$, and a field power term usually assumed to have the value b=0.5. The other features A* and $K_d$ lead to a field threshold, which is a controversial feature that is also found in [5]. The choice of expression encompasses all possible features and also poses a challenge to the method, and for this reason we have chosen to use it as an example to illustrate the application of the method. However in the context of cable geometry the chosen life model can be simplified by using either a known or calculated radial distribution of space charge. This will eliminate the assumption

relating space charge concentration to the local field and hence remove ‘b’ from the list of parameters. It should be noted however, that our choice of model was made strictly for convenience in testing and that the method can be applied to any life expression and is not restricted to the model chosen.

### 3.1 Details of fitting method

#### Data used

The method described in section 2 was used to fit the DMM life expression to experimental data from cable ageing experiments carried out for BICC Cables Ltd (now owned by Pirelli Cables Ltd.) [26]. Cables insulated with extruded XLPE of thickness 4.4mm were aged under nine different experimental conditions. Twelve cables were aged under each condition, and the tests were stopped after eight cables had failed. A Weibull analysis applicable to singly censored data was therefore carried out [23], resulting in B63 and $\beta$ values for each of the nine experimental conditions.

The cables were 15kV medium rated cables, with aluminium cores and values of $R_I$ and $R_O$ of 5.9mm and 10.3 mm respectively. They were all 9.14m long. Cables were aged at temperatures of 60°C, 75°C and 90°C and applied AC r.m.s. voltages of 34.6kV, 26kV and 17.3kV. The cables also contained thin semicon layers between the core and the insulation, though these were ignored for the purposes of the fitting. This is justifiable here, since the only effect of an extra layer would be to change the mean thermal and electrical resistivities of the insulation/semicon layer and in all cases the cables were aged under AC voltage, no current was applied to the cable cores, and the

temperature was assumed constant across the insulation. There was therefore no temperature gradient across the insulation – only an AC-type field gradient, which is independent of both the electrical and thermal resistivity of the insulating layer as shown in equation (2).

**Error function**

In order to fit experimental data to the DMM model, the following error function, representing the difference between experimental data and the model predictions, was minimised to find optimal DMM parameter values in $L_i$

$$\sum_J \left[ \left\{ \ln(B63_J) - \ln\left( \left[ \frac{N}{\sum_i \left( \frac{1}{L(r_i)^\beta} \right)} \right]^{\frac{1}{\beta}} \right)_J \right\}^2 \right] \qquad (21)$$

Above, J is the number of B63 values available. For each B63 value, the error function takes the difference between the log of the B63 value and the log of the hypothesised cable lifetime expression as in equation (19). The squares of the differences are summed over all experimental conditions to give the final error value for the whole data set. Natural logarithms are used in the error function due to the extreme non-linearity of the DMM equation. The square of the differences is used to avoid fits where the fit is good for most B63 values but very poor in one or two cases.

Equation (21) was minimised using a grid search method implemented using a FORTRAN computer program.

### Values of N and β

The number of shells used in this fitting, N, was 100. This value was chosen for several reasons. Firstly, N=100 corresponds to a situation where the thickest shells in the cable are roughly the same thickness as the PET films for which the DMM model has been previously shown to give a good fit [3]. Since the models were originally applied to thin films, ensuring that the shells are of a similar thickness ensures that the applicability of the expression demonstrated on thin films is retained. Secondly, N was chosen to be high enough to give as good a fit as possible to the data. Since the N dependence of the model parameters is eliminated in the fitting function, the only effect of increasing N should be to increase the quality of the fits due simply to an improved accuracy in the discrete representation of a continuous system. This effect was found to reach saturation at a value of N of approximately 100. The third criterion for a value of N is that it cannot be too large that the computation takes too much time.

A value for β also had to be chosen, since the error function requires only one value of beta. Each experimental condition yields its own value of β, and for the data used here the β values ranged from 2.4 to 8.5 – each with fairly wide confidence limits. We have assumed that each of these values is the same for each cable set so long as the ageing process is the same, so an average of all the β values was used. This average was weighted towards the smaller end, since the highest β was much higher than the other values and was therefore deemed atypical.

## 3.2 Results

The results obtained from fitting the DMM model to cable data as outlined above are shown in figure 2.

In figure 2, the y-axis represents time in seconds, and the x-axis shows applied RMS voltage in kV. B63 values from each of the nine conditions under which cables were aged are shown as crosses, circles and triangles corresponding to tests at 363K, 348K and 333K respectively. The 90% confidence limits for each B63 are shown as error bars. Each of the lines in figure 2 represents the lifetime predicted by the DMM model using the method described above. Each line shows predicted lifetime as a function of applied voltage at a temperature corresponding to one of the ageing temperatures. The lines show voltage threshold behaviour – i.e. below a threshold voltage, cables are predicted to have an infinite life. However, the cable lifetime only becomes infinite if the field and temperature experienced everywhere in the insulation – i.e. by each of the constituent shells - is below the threshold for the material.

The parameter values used to obtain the fits shown in figure 2 are given in table 1, along with the parameters from fitting to life data from other types of polymer specimen.

In the FORTRAN grid search used here, the DMM parameters were allowed to vary over wide ranges. The magnitudes of the model parameters obtained are nevertheless all similar in magnitude to those obtained in previous fittings to AC ageing data of XLPE mini-cables and PET thin films.

## 4. Discussion

### 4.1 Fit to data

The fit in figure 2 can be seen to be good, with the predicted lifetimes being within the 90% confidence limits of the experimental data for four out of the nine conditions. This is a good fit considering the assumptions involved in the derivation of the fitting method. The most significant of these assumptions is the way that the electrical field strength is used in the method – firstly the electric field in each shell is calculated on the basis of simplifying assumptions giving equation (2) and then this value is used in the DMM model in another assumed relationship describing the amount of charge in the material in terms of the local macroscopic field.

**4.2 Parameter values – volume considerations**

The magnitudes of the model parameters obtained are similar in magnitude to those obtained in previous fittings to AC ageing data. This suggests that the cable fitting method works well, and supports the contention that the ageing process is the same for each of the materials studied.

The parameters in table 1 were obtained from fits to AC ageing data involving very different specimen types. In this investigation, the cables were insulated with XLPE with a volume of $2x10^{-3}m^3$ and a thickness of 4.4mm. The mini-cables for which parameter values are quoted had an insulation thickness of 1.5mm, and a volume of approximately $3x10^{-6}m^3$. The volume of the PET films is not known, but the thickness of each was $50x10^{-6}$mm – implying a volume many times smaller than in either of the cable cases.

Any dependence of specimen lifetime on volume must be reflected in the magnitudes of the DMM parameter values obtained from fitting to data involving specimens of

different volumes. The question as to how the specimen volume affects parameter values in table 1, however, is not clear, since the parameters obtained are all for different materials, as well as for different volumes. This is true even of the XLPE cables evaluated here and the XLPE insulated mini-cables, since the XLPE was made by different cable manufacturers in each case, and there are therefore likely to be significant differences in composition between the two. It is therefore not possible to separate out differences in parameter values due to volume, from differences due to material morphology and chemical composition. The volume of insulation of the cables used here, however, is considerably larger than in the other two cases – almost 700 times larger than the mini-cable insulation, and likely to be much larger again than the PET films.

In spite of the material differences it is possible to use the parameter sets of table 1 to speculate as to which of the DMM model parameter values might be affected by volume. The common assumption that a larger volume of insulation will fail faster than a smaller volume under the same conditions is essentially based on a statistical argument (see for example [22,23]), i.e. bigger volumes give a greater preponderance of sites susceptible to ageing and hence a bigger likelihood of the existence of highly susceptible sites.

In the DMM models these sites are characterised by polymer moieties that can trap charge and respond to the trapped charge by surmounting an energy barrier to an alternative conformation corresponding to a local deformation. The influence of the local space charge is to both accelerate the local changes and to stabilise a more extreme local distortion than that which would have been produced at thermal

equilibrium in its absence. When the distortion exceeds a critical level it is assumed to initiate a rapid failure process. Differences in the parameter sets obtained for cable data as compared to the other two sets, particularly the mini-cables, may therefore relate to a greater severity of the most susceptible sites.

Since the temperature is constant across the radius of the cable in the samples whose failure data has been analysed (see section 3.1), a characteristic free energy barrier #G ($=H_{dk}-TS_d$) can be defined as for the thin film samples. As shown in Table 1 its value is actually very similar for all of the three systems, however it is clear that the component of the barrier arising from the activation enthalpy is greater in the full-scale cables than in the other two cases. This means that ageing is much more sensitive to temperature in the present cable data than for the other two systems. The changes in barrier factors $H_{dk}$ and $S_d$ cannot be regarded as a volume effect as we would expect larger volumes to lead to more susceptible sites, with smaller #G, over the temperature range experienced by the cable. It should be noted that the value of the activation entropy, $S_d$, is negative. This corresponds to a reaction in which the ground state is more configurationally disordered than the barrier state through which the reactants move to the product state. In this kind of reaction we can picture the reacting moieties having to adopt specific orientations and bond angles in order to achieve passage through the barrier. This requires work to be done on the group of entities that have to pass through the barrier. The similarity in #G values appears to be an instance of a compensation law and is also found for the ageing of PET films [1-4], where #G is found to be the same in DC and AC ageing over the temperature range measured. It is possible to speculate that this result indicates that the basic features of the ageing mechanism are the same in all cases, but that the free energy surface

changes with frequency and morphology. More specifically it would appear that as the amount of ordering required to enter the barrier state becomes smaller (i.e. $S_d$ moves closer to zero) the system is forced to surmount a higher enthalpy barrier, i.e. the disordered state has a large enthalpy barrier but ordering allows reaction via a smaller entropy barrier at the expense of the free energy required for the ordering.

It is possible that the parameter A* may be affected by volume. A* is the fraction of moieties that must be involved in deformation for breakdown to occur in any localised area. It seems likely that this fraction might vary from region to region of the specimen. This means that in a larger volume of polymer there may be an increased likelihood of finding regions where fewer moieties need to be involved for breakdown to be initiated. As a result, a specimen with a larger volume will require the conversion of fewer moieties to initiate failure, and consequently a smaller local energy concentration will be required. The differences in characteristic A* shown in table 1 seem to support the hypothesis that the specimens with larger volumes require fewer moieties to be converted, and therefore lower energy concentration, to initiate breakdown. Larger volumes would therefore experience a reduction in lifetime under a given condition.

$C_d$ and b describe the effect of a field on the barrier to ageing, #G. On the application of an electrical field of magnitude E, #G is reduced by an amount equal to $C_dE^{4b}$, and this acts to accelerate the ageing reaction. Large values of $C_d$ and b for a set of specimens therefore indicate that the ageing reaction is accelerated strongly by the electrical field. In addition, this field dependent energy helps to stabilise the state of the moiety corresponding to the deformed polymer and hence facilitates the

achievement of sufficient deformation to initiate failure. A greater volume of polymer is more likely to contain sites at which this is the case – i.e. sites at which the field can have a strong influence on the ageing process. In the DMM model such sites will be those that have greater ability to trap charge and store electro-mechanical energy. They may therefore be sites that have a bigger electrostriction coefficient than the average for the specimen. Such sites may also (or instead) have a smaller bulk modulus or relative permittivity than average. Microscopic variations in macroscopic material characteristics such as these seem very likely, which makes these two parameters likely to have a volume dependency. The data in table 1 seems to support this to some extent, with the largest polymer volume showing by far the largest values of $C_d$. The values of b are all quite similar, however, with no observable pattern with volume. Overall, the $C_dE^{4b}$ term for fields from 0 to 20kV/mm is always largest for the XLPE cable parameters. The same term is larger for the mini-cables than for the thin films for all fields above about 3kV/mm, but below this field the values are very similar. These parameters are also likely to be strongly material dependent, however, so this is by no means conclusive.

### 4.3 Relationship to Space Charge

The DMM ageing theory differs from the other models [5-14] in ascribing the ageing to energy (electromechanical) concentration produced by trapped space charges. The local energy is proportional to either the $4^{th}$ power of the space charge field or its square depending upon whether or not the local centre was assumed to behave as a region with macroscopic properties or as an irreducible volume element with atomistic/molecular properties [27]. The relationship to the known applied field was made via the assumption that the trapped charge $q \propto E^b$ where E is the applied field.

The physics behind the model [1] therefore allows the possibility that a direct measurement of space charge could be used instead of estimation of $E(r_i)$. This has the benefit of eliminating the exponent b as a parameter, since the local space charge field can be taken to be proportional to the space charge density. The effect of local field would still be expressed through a parameter like $C_d$. One drawback to this course of action is that trapped charges may be present though their net value may be zero. The energy concentration and local field would still exist on the atomistic scale even though the measured space charge would be zero. Secondly, the divergence of the applied Laplacian field in cables would also yield an electromechanical energy concentration [5] that would have to be added to the atomistic value. In order to pursue this approach space charge measurements would have to be taken during ageing and this information is not yet available.

## 5. Conclusions

The radial variation of temperature and electric field experienced in cable geometry can be included in an ageing theory by means of a shell approach. The methodology can be applied to any ageing theory and can, in principle, be used to predict cable lifetimes from thin film experiments. In practice it is better suited to investigating the volume dependence of ageing parameters.

The methodology has been applied to the life expression of the DMM model, which was found to fit the data very well. It was shown that values of the A* and $C_d$ parameters correspond to a characteristic centre that is more susceptible to ageing, as would be expected for a system whose insulation had a bigger volume. The free energy barrier to ageing had almost the same value as for mini-cables, but the

activation enthalpy component was bigger, It therefore seems possible to conclude that the larger cable contains centres that require less energy concentration to achieve the initiation of failure, that the centres are more susceptible to the affect of an electrical field, but that the barrier to the ageing reaction involves different routes across the free energy surface corresponding to differences in the local morphology.

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# BIOGRAPHIES

## *Elizabeth Cooper*

Elizabeth Cooper was born in the UK in 1976 and gained a degree in Physics with Astrophysics from the University of Leicester in 1999. In 2002 she received a PhD, also from the University of Leicester. She currently works with Professors Dissado and Fothergill in the high voltage laboratory of the engineering department at Leicester, researching the physical processes relevant to charge movement in the insulation of high voltage DC power cables.

## *Len A Dissado (Senior Member since 1996)*

Len Dissado graduated from University College London with a 1st Class degree in Chemistry in 1963 and was awarded a PhD in Theoretical Chemistry in 1966 and DSc in 1990. After rotating between Australia and England twice he settled in at Chelsea College in 1977 to carry out research into dielectrics. His interest in breakdown and associated topics began with a consultancy with STL began in 1981. Since then he has published many papers and one book, together with John Fothergill, in this area. In 1995 he moved to The University of Leicester, and was promoted to Professor in 1998. He has been a visiting Professor at The University Pierre and Marie Curie in Paris, Paul Sabatier University in Toulouse, and Nagoya University, and has given numerous invited lectures, the most recent of which was the E.O.Forster Memorial lecture at ICSD'7 in Eindhoven. Currently he is an Associate Editor of IEEE Transactions DEI, and co-chair of the Multifactor Aging Committee.

## *John C Fothergill (Senior Member since 1995)*

Professor Fothergill was born in Malta in 1953. He graduated from the University of Wales, Bangor, in 1975 with a Batchelor's degree in Electronics. He continued at the same institution, working with Pethig and Lewis, gaining a Master's degree in Electrical Materials and Devices in 1976 and doctorate in the Electronic Properties of Biopolymers in 1979. Following this he worked as a senior research engineer leading research in electrical power cables at STL, Harlow, UK. In 1984 he moved to the University of Leicester as a lecturer. He now has a personal chair in Engineering and is currently Pro-Vice-Chancellor.

# Table and Figure captions

**Table 1** – Parameter values from fitting the DMM model to data. #G is the activation free energy ($=H_{dk}$-$TS_d$) at the temperatures quoted.

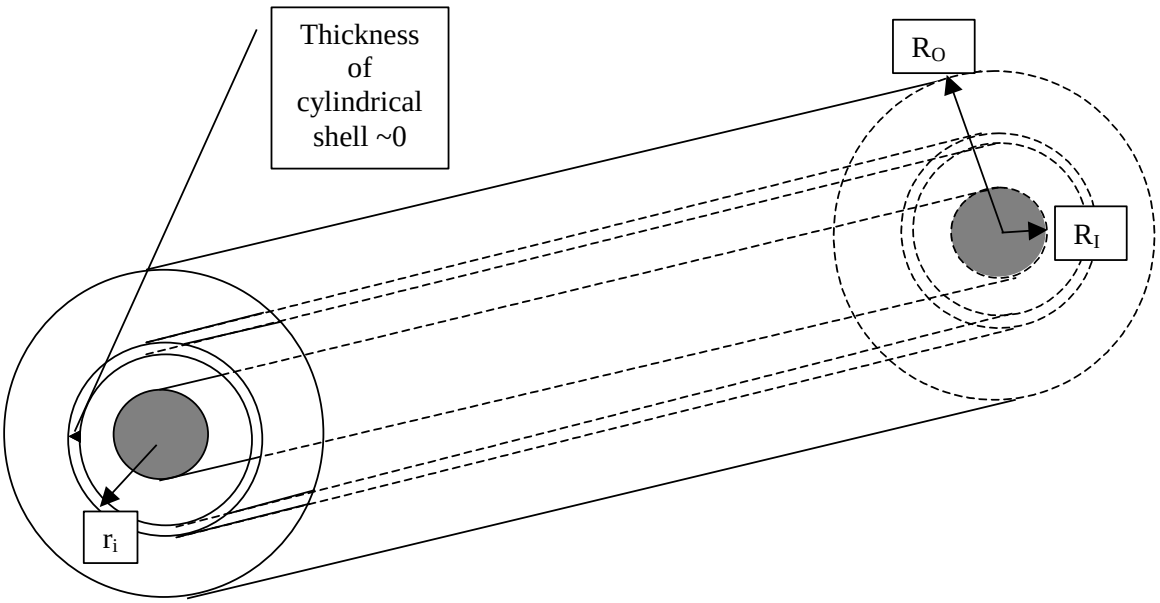
**Figure 1** – Typical coaxial cable geometry with an example shell shown at radius $r_i$

**Figure 2** – Experimental lifetime data with lifelines predicted by the DMM model

| **Table 1** | Parameters from this investigation | Parameters for AC ageing of thin film PET [4] | Parameters for AC ageing of XLPE insulated mini-cables [4] |
|---|---|---|---|
| Sd (J/K) | -3.8E-22 | -5.2E-22 | -5.6E-22 |
| Hdk (K) | 6333 | 1274 | 1448 |
| Kd (K) | 292 | 103 | 229 |
| $C_d$ (J(mm/kV)$^{4b}$) | 3.833 | 1.593 | 1.376 |
| A* | 0.325 | 0.485 | 0.38 |
| b | 0.400 | 0.39 | 0.425 |
| #G (J) T=20°C<br>T=100°C | 2.0E-19<br>2.3E-19 | 1.7E-19<br>2.1E-19 | 1.8E-19<br>2.3E-19 |

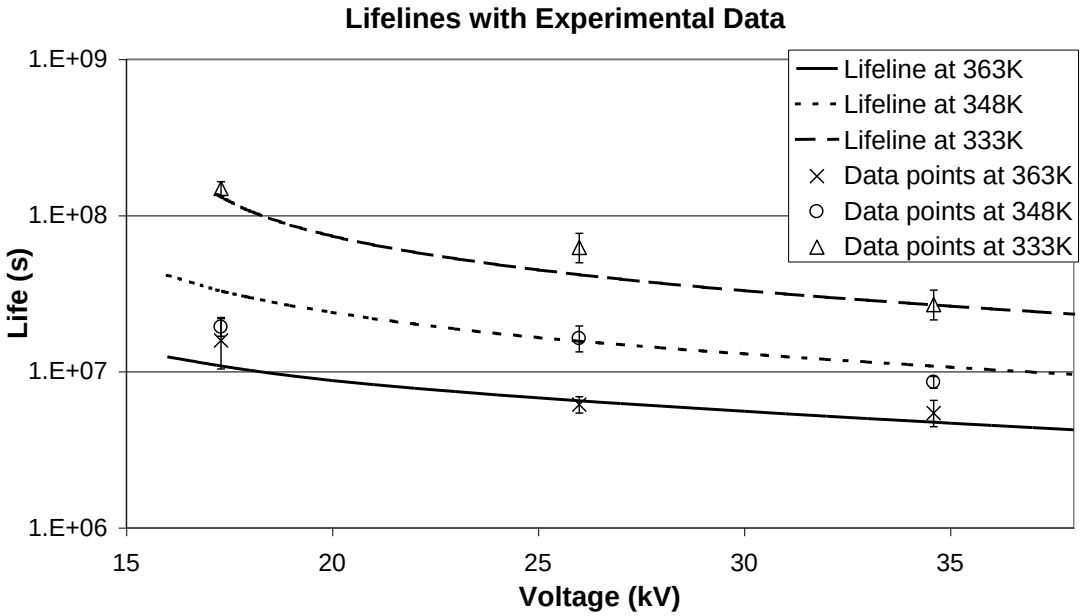
1

[1] Application of thermoelectric ageing models to polymeric insulation in cable geometry
ES Cooper, LA Dissado, JC Fothergill 27th May 2003
**Table 1**




2

[2] Application of thermoelectric ageing models to polymeric insulation in cable geometry
ES Cooper, LA Dissado, JC Fothergill 27th May 2003
**Figure 1**




[3]

[3] Application of thermoelectric ageing models to polymeric insulation in cable geometry
ES Cooper, LA Dissado, JC Fothergill 27th May 2003
**Figure 2**